



The impact of atmospheric stability on wake losses

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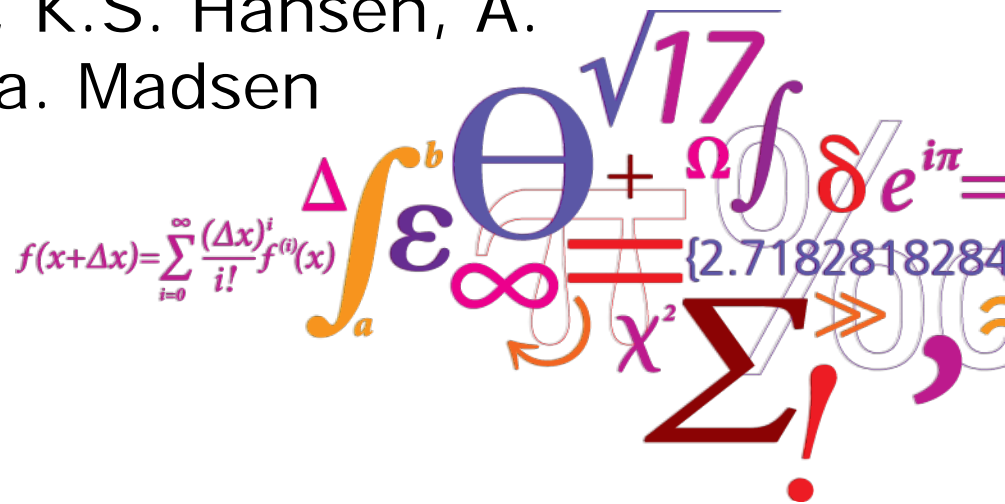
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The impact of atmospheric stability on wake losses

G.C. Larsen, T.J. Larsen, K.S. Hansen, A. Chougule, J. Mann, H. Aa. Madsen



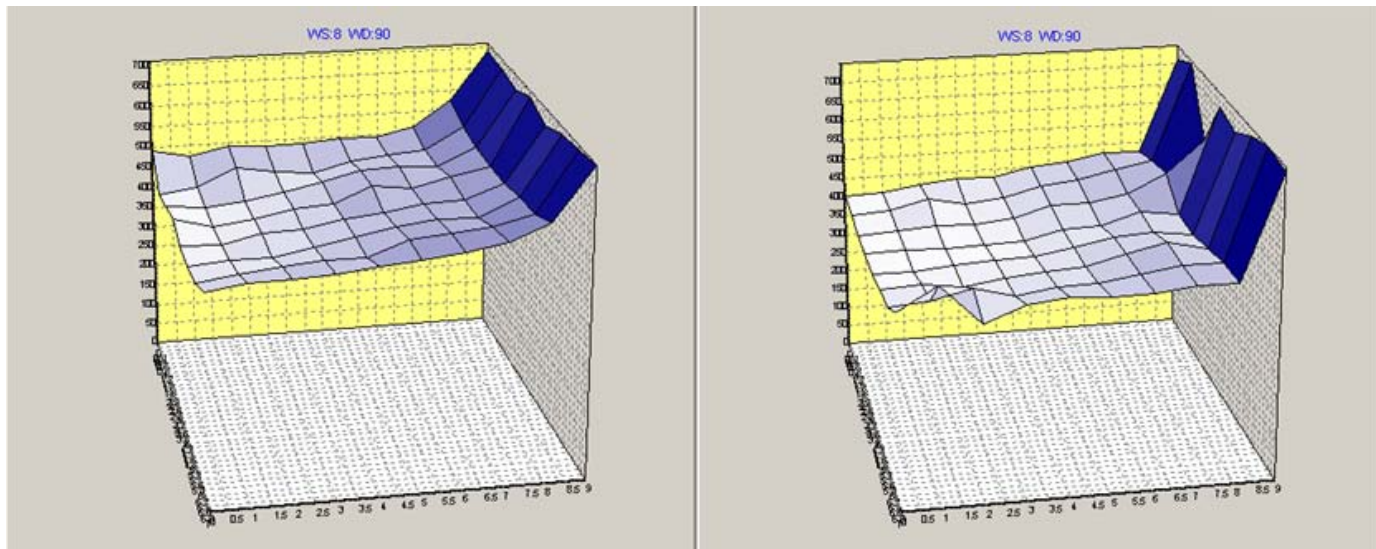
A collage of colorful mathematical symbols including integrals, summations, and various Greek letters.

Outline

- Introduction
- Basic considerations
- Hypothesis
- Model
- Definition of case
- Simulation characteristics
- Results
- Conclusions
- Future work
- Acknowledgements

Introduction

- Analyses of full-scale measurements from Danish (offshore) wind farms have shown a significant dependence of wake losses on atm. stability conditions [e.g. L. Jensen; EWEC 2007]
- Horns Rev; 8m/s; 90 deg.; un-stable ctr. stable



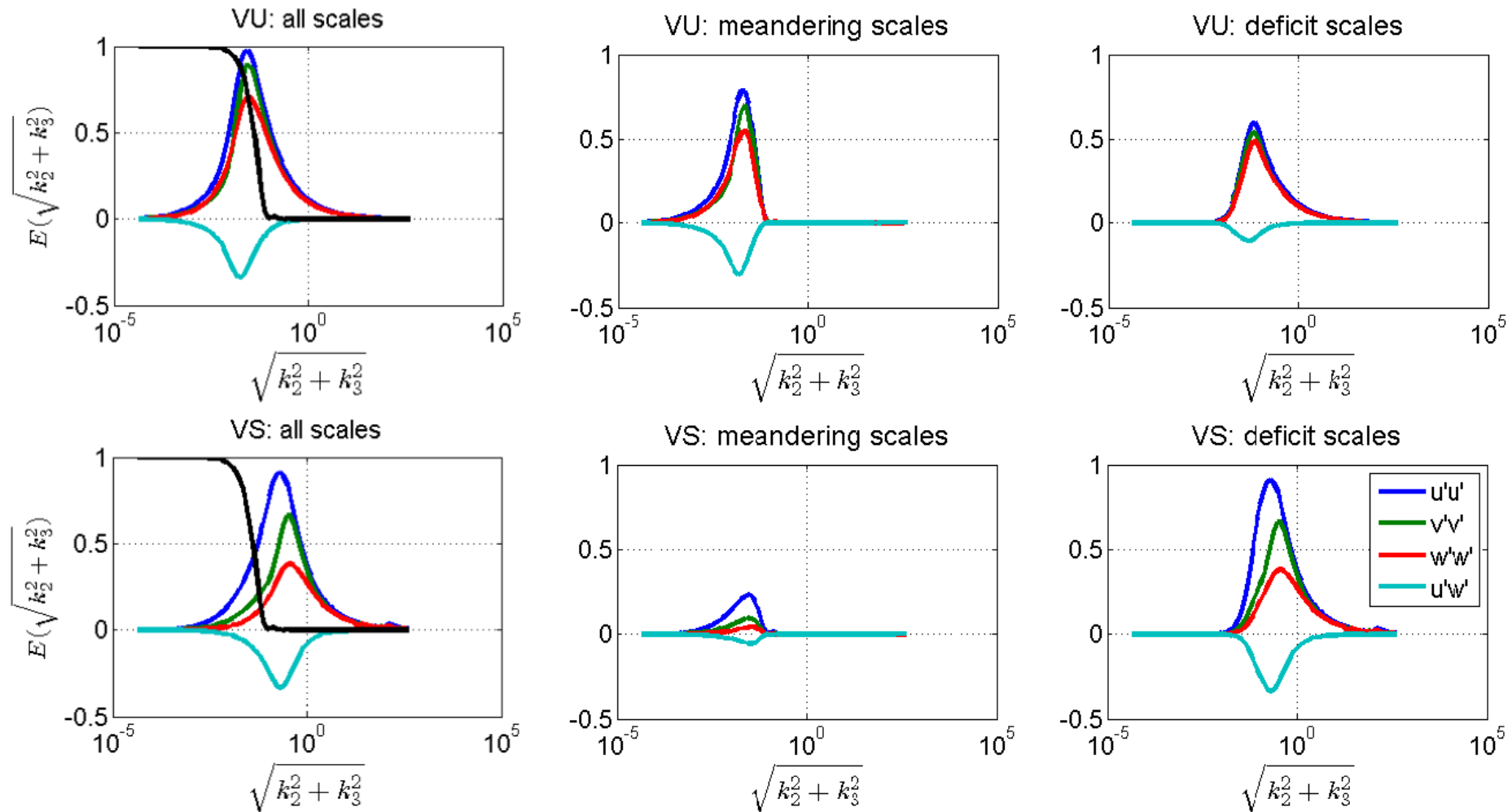
Basic considerations

- Atmospheric stability affects turbulence *level* and turbulence *structure*
 - *Field data* from the OWEZ and the North Hoyle offshore wind farms demonstrates the importance turbulence structure only (binning: U; TI; stab. Class). Losses ~10% higher for VS than VUS [Keck et. al. 2012]
 - *AL-LES simulations* with OpenFOAM in neutral and very unstable atmospheric conditions and constant TI give similar results as based on WT power curve

Hypothesis (1)

- Free shear flows, as wakes, are usually "narrow" ... and we believe that the observed wake loss dependence on ABL stability conditions is primary dictated by a combination of:
 - Stability impacting the low frequency part of the atmospheric turbulence ... and thus the large-scale turbulent structures (driving the meandering)
 - Wake meandering being driven by large-scale turbulent eddies

Hypothesis (2)



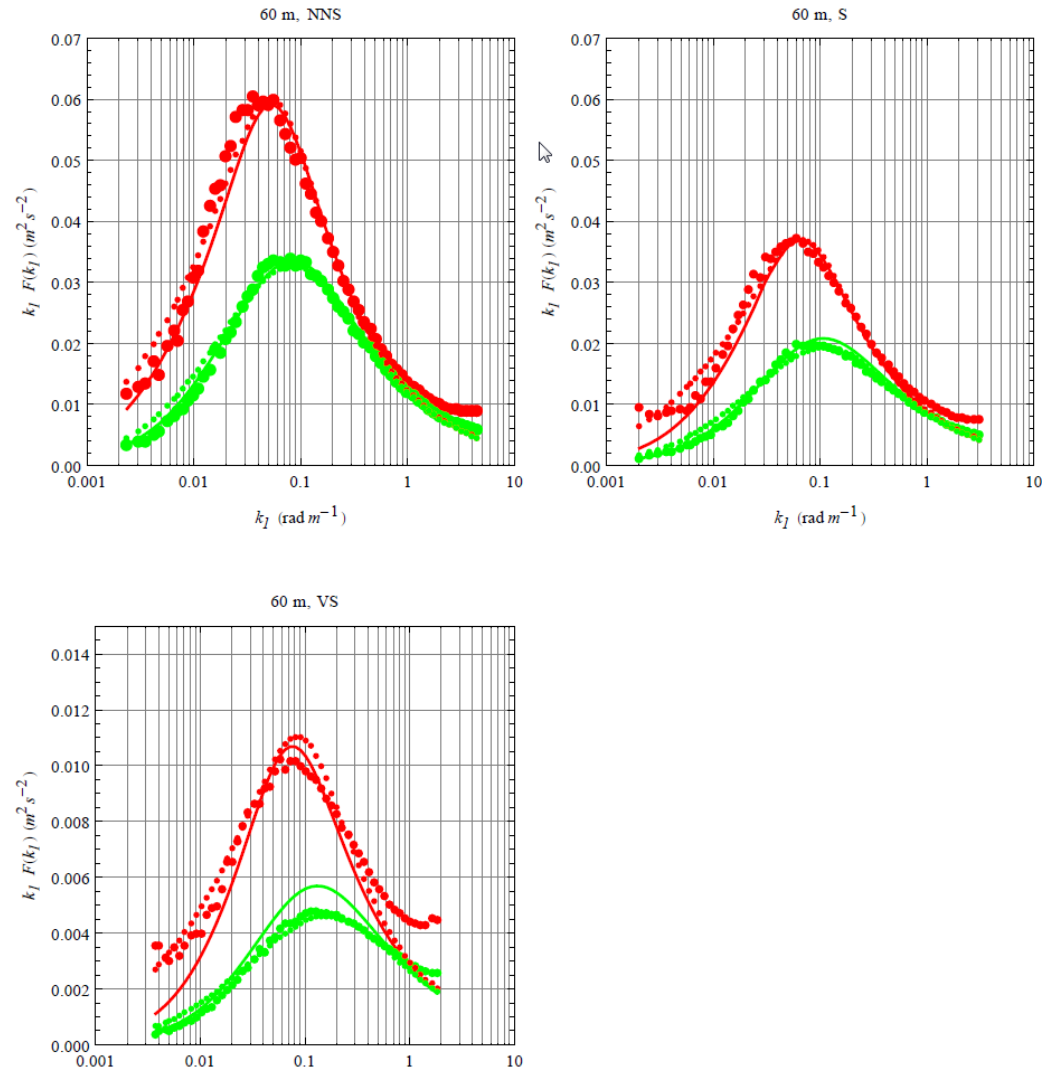
Model (1)

- Dynamic Wake Meandering (DWM) model approach for the wake flow field; i.e. based on a split in turbulent scales ... with
 - Small scales being responsible for wake *attenuation* and expansion; and
 - Large scales being responsible for stochastic *wake meandering* by moving wake “releases” as passive tracers in ABL turbulence
- Aeroelastic simulations (HAWC2) using DWM generated inflow conditions ... thus enabling *full aerodynamic representation* of rotor performance incl. *control* ... thus essentially the “Poor man’s LES ACL”

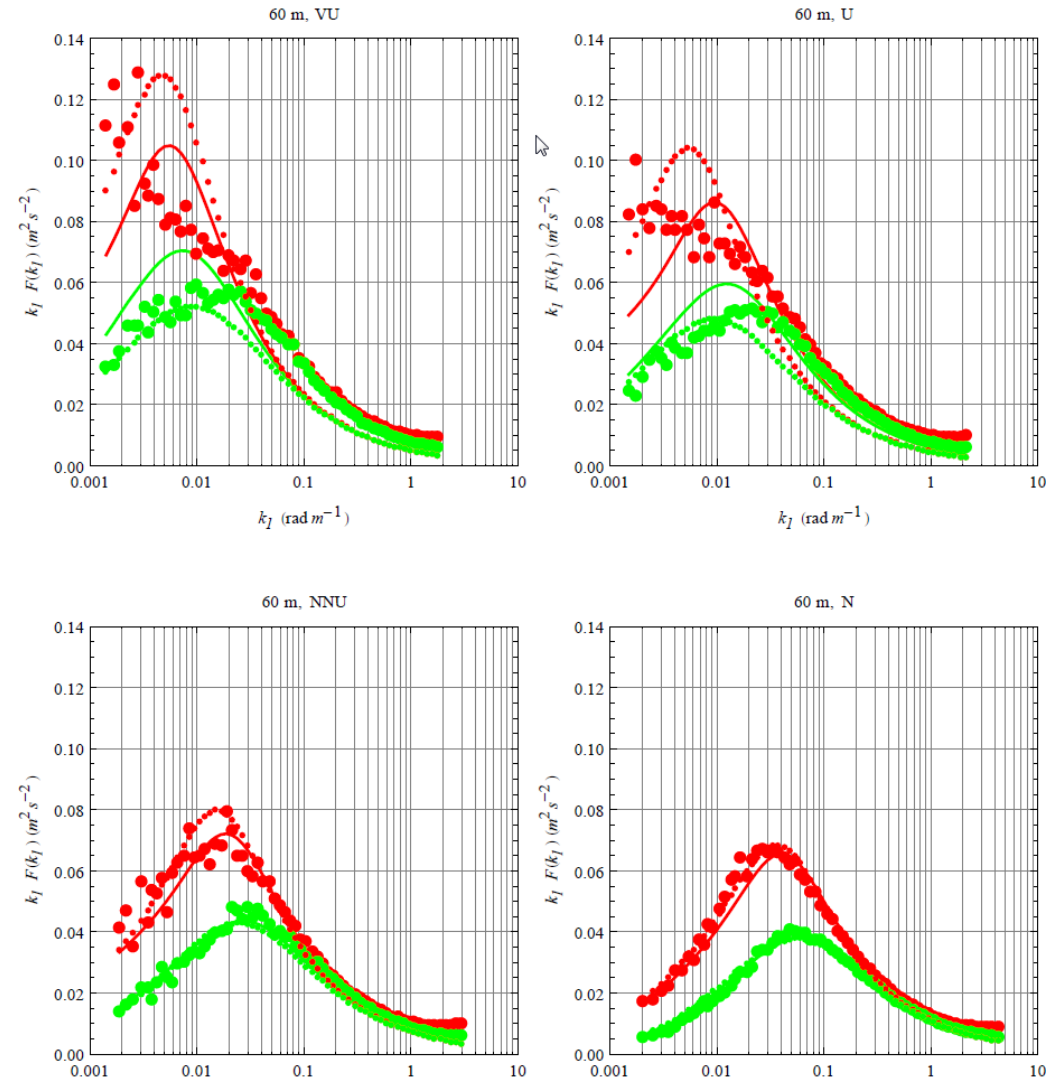
Model (3)

- Mann “classic” spectral tensor ... and a newly developed generalization including buoyancy effects (i.e. temperature effects) used to model turbulence:
 - One-point fits (i.e. sonic data)
 - Mann “classic” spectral tensor ($\alpha \epsilon^{2/3}$; Γ ; L) fitted to Høvsøre data (vv , ww ... but excluding uu and uw). Violating neutral stab. assumption!
 - Generalized spectral tensor ($\alpha \epsilon^{2/3}$; Γ ; L ; + 2 additional parameters) fitted to Høvsøre data: Full Reynolds stress tensor (uu , vv , ww , uw , tt , ut , wt)

Model (4)



Model (5)

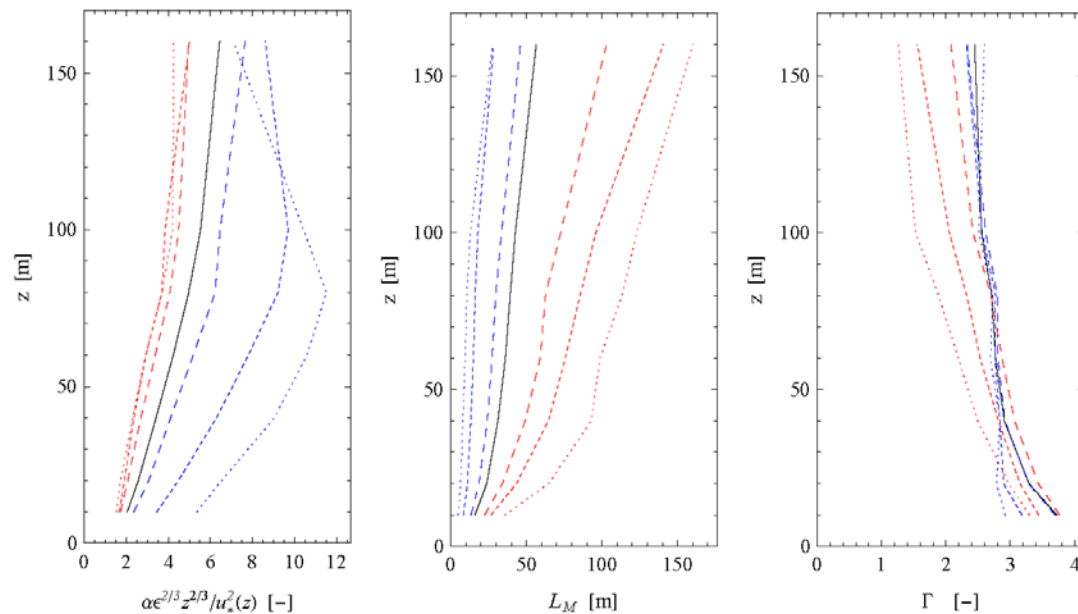


Model (6)

- ABL stability classified into 7 pre-defined stability classes (Obukhov length) [Pena et al.]:
 - Very stable: $10 \leq L < 50$
 - Stable: $50 \leq L < 200$
 - Near neutral/stable: $200 \leq L < 500$
 - Neutral: $|L| \geq 500$
 - Near neutral/unstable: $-500 < L \leq -200$
 - Unstable: $-200 < L \leq -100$
 - Very unstable: $-100 < L \leq -50$

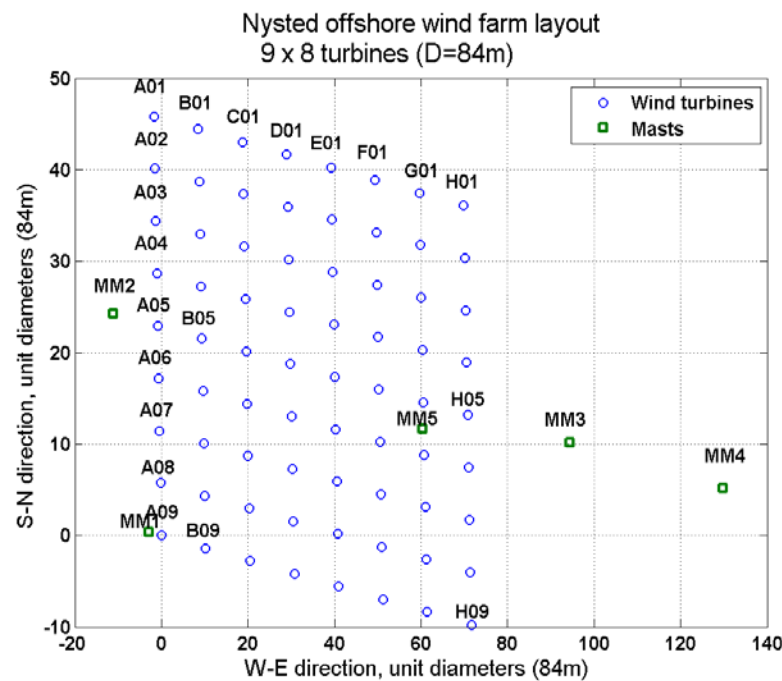
Model (7)

- Spectral tensor parameters depends on height ... in this study the parameters for 60m is chosen



Definition of case (1)

- Nysted wind farm - 72 2.3 MW Siemens WT's



- Meteorological data (U, direction): MM2

Definition of case (2)

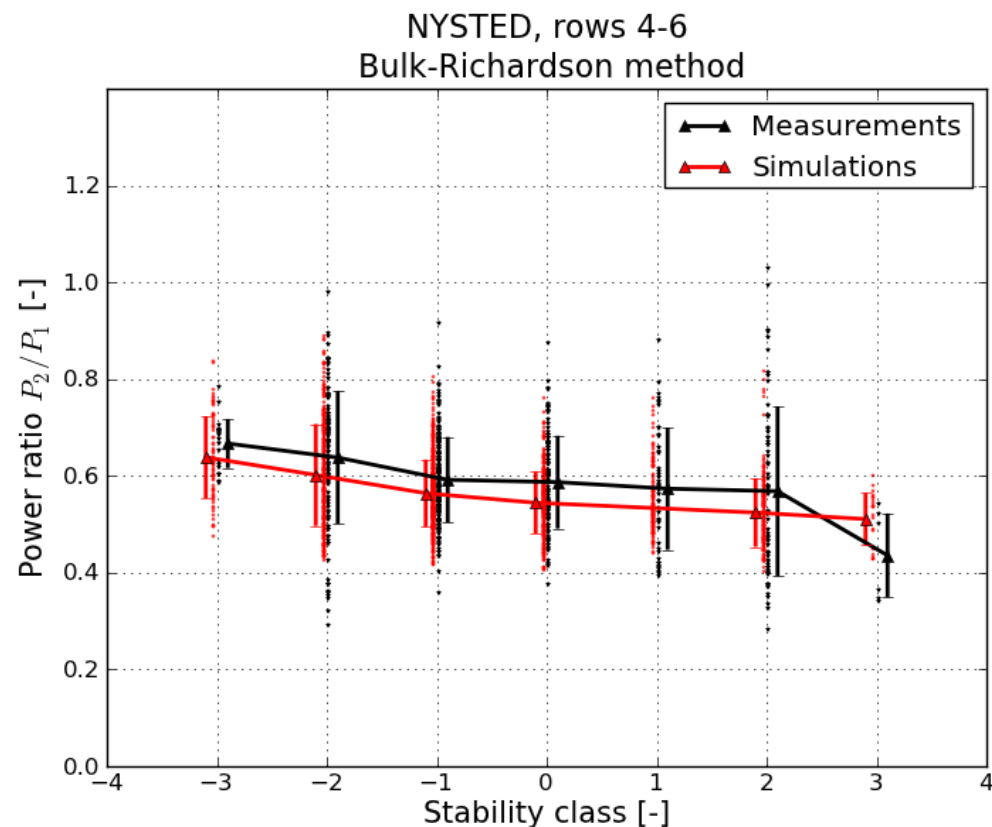
- Relative production of second turbine in a wind farm row considered ... restricted to pairs A04/A14; A05/A15; A06/A16 to reduce large scale effects
- Mean wind speed bin: [8; 10] m/s
- Mean wind direction: Along row; i.e. $277.6^{\circ} \pm 2^{\circ}$
- Turbine spacing (in this direction): 10.3 D

Simulation characteristics

- All observed mean wind directions within the selected direction bin simulated ... thus based on MM2 observations within $277.6^{\circ} \pm 2^{\circ}$
- All observed mean wind speeds within the selected direction bin simulated ... thus based on MM2 observations in [8; 10] m/s
- Thus, 555 A04/A14; A05/A15; A06/A16 wake cases simulated – each with different turbulence seeds

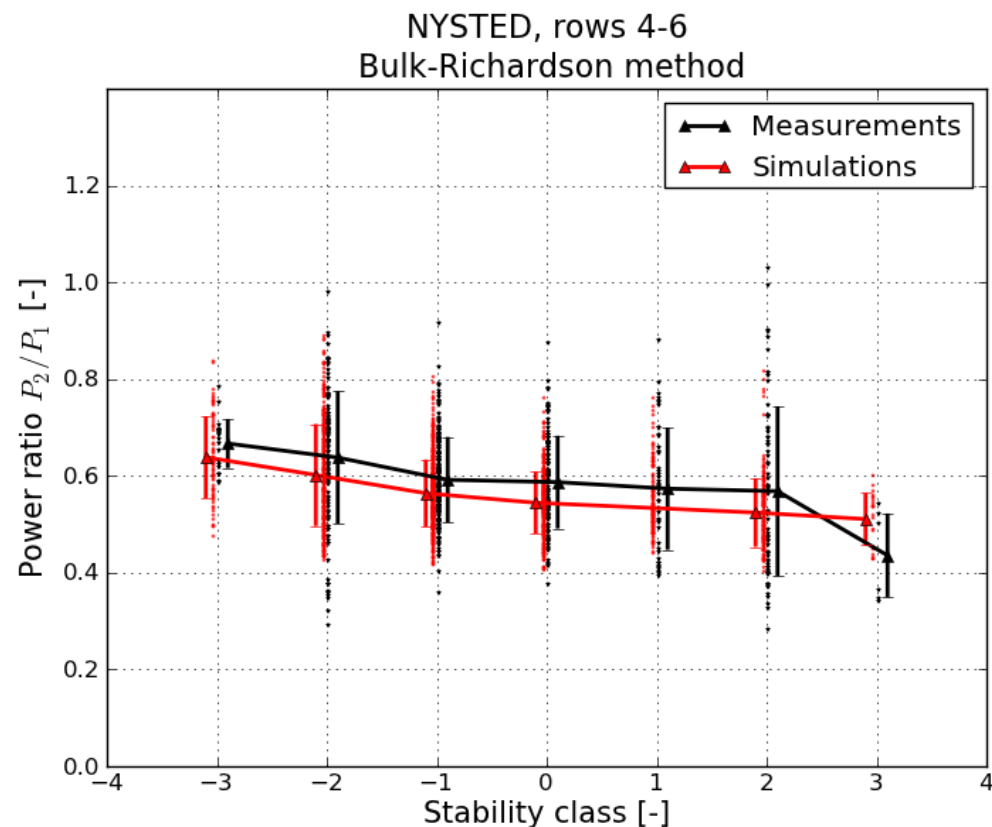
Results (1)

- DWM using "classic" Mann spectral tensor



Results (2)

- DWM using generalized spectral tensor

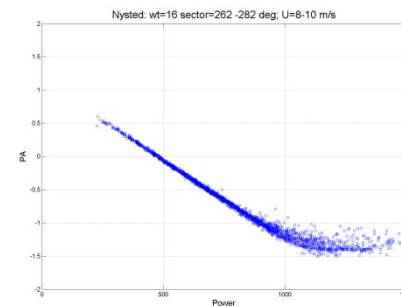
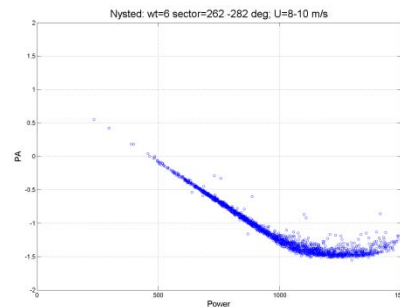


Conclusions (1)

- Mann spectral tensor can be fitted to atmospheric stability conditions other than neutral ... if only turbulence components v and w is of interest
- However, low frequency part of U and VU spectra should be investigated in more detail ... measured as well as simulated
- The generalized spectral tensor fitted to the full 4x4 Reynolds stress tensor (i.e. uu , vv , ww , uw , tt , ut , wt) performs qualitatively as the “restricted” fit of Mann spectral tensor ... although some differences in the case of U and VU conditions are observed

Conclusions (2)

- General trend in power ratio is captured ... but simulated power ratio is less than the measured values, although within the uncertainty band defined by $\pm\sigma$
- Deviation in power ratio level may be related to differences in turbine pitching



- Simulated relative effect of ABL stability also very similar to full scale observations from the OWEZ and North Hoyle studies (i.e. wake losses $\sim 10\%$ higher for VS than VUS)

Future work

- Analysis of production losses of *all* turbines in a row for the simple along-row flow case
- Analysis of more complex flow cases, where the mean wind direction forms an angle (different from zero) with the direction of the rows – i.e. “oblique” inflow
- Analysis of wind farm production losses integrated over all (mean) wind directions
- Investigation of fatigue load dependence on ABL stability
- Experimentally based determination of meandering pattern’s for various stability conditions as based on the Risø Tellus 2D LiDAR experiment

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The EUDP project “Impact of atmospheric stability conditions on wind farm loading and production”, under contract 64010-0462, is acknowledged for financial support and thus for making this study possible